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THEORETICAL & EXPERIMENTAL INVESTIGATION OF COHERENT STRUCTURE --ETC(U)
MAY 80 D E ABBOTT, C R SMITH, J D WALKER F49620-78-C-0071
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18. SUPPLEMENTARY NOTES

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COHERENT STRUCTURE
FLOW VISUALIZATION
NUMERICAL MODELLING
VORTEX-WALL INTERACTIONS

(400000)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This project combines both experimental video flow visualization studies and theoretical investigations of a series of phenomenological and theoretical models based upon the three-dimensional details of convected, coherent structural elements of a turbulent flow as it interacts with a solid surface. The progress over the past year has led to the experimental consideration of range of sub-problems including high Reynolds Number (4×10^6) turbulent flows, the effect of surface modification on low-speed streak formation, and the effect

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of vortex loop interaction with a solid boundary. To augment the visualization pictures, a computerized video-digitizing system has been developed. Preliminary results show tremendous promise for obtaining quantitative data from flow visualization pictures. The specific thrust of the theoretical studies has been focussed on three areas: (1) how two- and three-dimensional vortex structures interact with wall boundary layers, (2) the development of a new type of prediction method for two-dimensional turbulent boundary-layer flows, and (3) improvement in numerical techniques for solving parabolic, boundary-layer equations.

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AFOSR-TR- 80-0567

Annual Scientific Report

on the

THEORETICAL & EXPERIMENTAL INVESTIGATION OF COHERENT STRUCTURE IN THE TURBULENT BOUNDARY LAYER

AFOSR Contract No. F49620-78-C-0071

Reporting Period 1 May 1979 to 30 May 1980

by

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RESEARCH OBJECTIVES

From an overall perspective, the objective of this research program is to obtain a clear physical and theoretical understanding of the dynamics of the turbulent boundary layer which will ultimately provide improved models for the turbulence quantities in the time-mean boundary-layer equations. The long range goals of the program continue to be both the improvement of the turbulent boundary-layer prediction methods and development of rational methods for control and/or modification of turbulent boundary layer behavior.

RESEARCH APPROACH

This project combines both experimental video flow visualization studies and theoretical investigations of a series of phenomenological and theoretical models based upon the three-dimensional details of convected, coherent structural elements of a turbulent flow as it interacts with a solid surface. The progress over the past year has led to the experimental consideration of range of sub-problems including high Reynolds Number (4×10^6) turbulent flows, the effect of surface modification on low speed streak formation, and the effect of vortex loop interaction with a solid boundary. To augment the visualization pictures,a computerized video-digitizing system has been developed. Preliminary results show tremendous promise for obtaining quantitative data from flow visualization pictures. The specific thrust of the theoretical studies has been focussed on three areas: 1) how two-and three-dimensional vortex structures interact with wall boundary layers, 2) the development of a new type of prediction method for two-dimensional turbulent boundary-layer flows, and 3) improvement in numerical techniques for solving parabolic, boundary-layer equations.

SCIENTIFIC RESULTS

Experiment

The high speed INSTAR IV Video System obtained under the present funding has been fully integrated with the water channel system and has provided a capability for viewing very small-scale flow structure with unusual clarity. Employment of the two-camera, split-screen technique has proven useful in determining three-dimensional flow structure characteristics, and coupled with a recently acquired fiber optic lens, has provided pictures of axial flow structure never before possible. In addition, a video digitizer-minicomputer system has been developed which allows entire video pictures to be rapidly converted into quantitative velocity field information.

During the last twelve months, work has progressed on four different experimental phases. First, detailed studies have been made of the wall-layer, low-speed streak phenomena, with its characteristics visually

documented over a much wider range of Reynolds numbers. In particular, streak spacing has been found not to be constant at a $y^+ \cong 100$, but to increase slightly with Reynolds number. In addition, through the use of the fiber-optic lens, the wall region and the inherent low speed streak structures have been examined using streamwise views taken immediately downstream of the phenomena using both dye and horizontal hydrogen bubble wires. By split-screening the streamwise view with a conventional plan-view of the streak structure, it has been observed that low speed streaks are always regions of lifted wall region fluid which result from the presence of longitudinal vortices very near ($y^+ \sim 20$ to 30) the wall. Additionally, it has been observed that these longitudinal vortices frequently appear in counter-rotating pairs, which appear to result from formation of small loop-like vortex structures during the bursting process. Extensive documentation of these axial vortices has been done for a number of characteristics including frequency of occurrence, vorticity, diameter, and location. The general conclusion from these studies are that:

1) vortex strength increases from the wall outward to $y + \approx 20\text{-}30$ and then decreases,

2) vortex diameter increases with distance from the wall after $y + = 10\text{-}20$,

3) spacing of vortex pairs increases with distance from the wall,

4) generally, vortex diameter appears to vary inversely with some function of vortex strength.

Second, in an effort to understand and isolate the apparent small loop-like structures near the wall, studies are being done of symmetric roughness elements which promote very controlled, clean transition to turbulence. Several single and dual view studies of single hemispherical transition elements have been done. Initial results show that the nested loop structures generated by the hemisphere element result in the formation of both low-speed streaks and "flow pockets" as are commonly observed in fully turbulent boundary layers. In addition, a well controlled cascading effect can be observed by which the nested loops grow laterally in typically turbulent spot fashion. In conjunction with this study, a detailed study of the effect of "rational" modifications of the boundary surface on streak formation and breakdown has been initiated. Preliminary results are quite promising, since they indicate that by insertion of longitudinal rods of diameter $d^+ \cong 10$ (scaled in boundary layer wall units), the spacing of the low speed streaks can be controlled (up to $\Delta Z^+ \cong 200$) by the rod spacing. In addition, it appears that the rod produced streaks in essence "take over" for the natural streaks and supplant them. One of the major ramifications of this streak control process is the potential for modifying (increasing, and possibly decreasing) drag, heat transfer, and mass transfer effects beneath a turbulent boundary layer. These studies are continuing.

Third, studies have been done of inviscid-viscous interaction by focusing on the response of fluid at a surface to an impinging loop vortex. In a quiescent environment, the impact of a loop vortex with the surface is observed to create a secondary loop of opposite rotation - a result which is predicted by the theoretical analysis. When the loop is generated in the flow above a developing boundary layer, the impact of the vortex with the wall again results in a secondary loop of opposite sign, however, both loops are asymmetrically skewed by the mean shear of the developing boundary layer. In addition, further studies have shown that for more energetic vortices, a third loop of the same sign as the second loop forms, apparently by means of the same mechanism as the second loop. A particularly important observation of this multiple loop formation is that once formed, the secondary and tertiary loops wrap quickly around the primary loop in a complex three-dimensional manner. This wrapping-up process both 1) rapidly dissipates the initial vorticity of the primary vortex and 2) acts as a mechanism for quickly dissipating the energy contained in the primary vortex away from the plate.

The fourth experimental phase has been the development and implementation of a system which allows the flow visualization pictures recorded on video tape to be digitized and stored, and processed for quantitative data by a minicomputer. A system has been developed which will digitize individual video frames as a 200 X 200 brightness array with a range of 256 brightness levels at the rate of one frame every 30 seconds. These digitized arrays are then scanned using an appropriate algorithm to determine relative motion from one frame to the next. Thus, by scanning a series of frames, velocity field behavior may be obtained as a function of time. At the present time, programs to perform the scanning and data reduction procedure are being completed and will be implemented before the end of the summer.

Analysis

During the past year, it has been conclusively demonstrated that a boundary layer responds to the motion of a two-dimensional vortex in such a way so that a violent eruption of boundary layer fluid occurs. In the analytical program, work was completed on the boundary layer effects induced by the motion of a vortex convected in the shear flow illustrated schematically in Figure 1(a); the situation illustrated in this figure was selected to simulate the environment experienced by a filament of vorticity in the outer region of a turbulent boundary layer. A considerable number of situations were considered corresponding to different vortex strengths and distances of the vortex from the wall; the results (for a typical example, see Figure 1(b)) point to a rapid and violent eruption of the boundary layer flow in all cases.

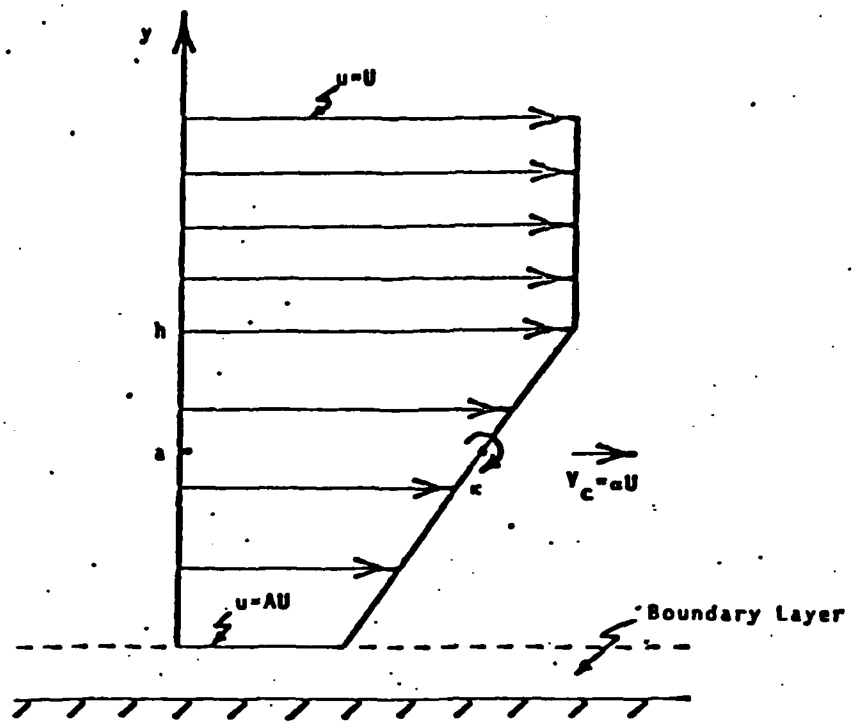

Figure 1(a) Sketch of geometry and construction of inviscid flow due to a vortex of negative rotation convected to the right above an infinite plane wall in a shear flow.

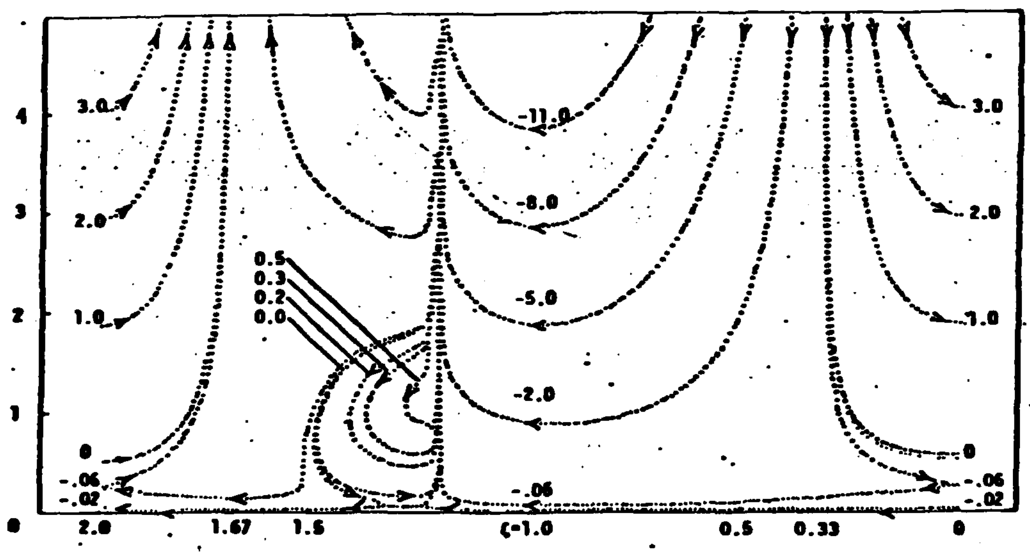

Figure 1(b). Instantaneous streamlines in the boundary layer relative to the vortex for A = .65, θ = .1, α = .2 at t = .725.
(Labels correspond to lines of constant Ψ.)

These results as well as a series of experimental confirmations of the phenomenon have led to a proposed physical mechanism for how vorticular structures, in a turbulent boundary layer and in a boundary layer undergoing transition, are able to regenerate structures similar to themselves; the proposed mechanism is illustrated schematically in Figure 2, which is reproduced from publication [3].

In the studies reported in publications [2] and [3], the response of a boundary layer to two-dimensional vortices convected in a uniform flow and shear flow, respectively, was examined. In all cases, it was found that the boundary layer responds to the vortex motion so that a boundary layer eruption will occur. However, an important element which is absent in two-dimensional vortex motion and which is believed to be an important physical mechanism in turbulent boundary layers is vortex stretching. An important question, therefore, arises as to whether or not the effect of vortex stretching in three dimensions can obviate the basic boundary layer eruption phenomenon which has been discovered and documented in this program for two dimensional flows. To answer this question and to extend the vortex interaction studies to three dimensional flows, work has been underway this past year in determining the effect of a circular ring vortex on a wall boundary layer as the vortex approaches the wall. It has been determined a circular ring approaching a wall in an otherwise stagnant fluid induces a secondary separation in the wall boundary layer leading to a violent boundary layer eruption. The results of the theoretical calculations have been compared against the results of a complementary set of experiments and excellent agreement has been obtained. Furthermore, it appears that a main effect of vortex stretching is to intensify and hasten the unsteady boundary layer eruption effect. At present, work is underway in investigating the effects of a vortex ring and vortex loops convected in a shear flow.

During the past year, work has progressed in the development of prediction methods for turbulent boundary layers with and without heat transfer. In Figure 3 some results are given; the data in the figure is for a turbulent boundary layer with heat transfer at the wall in an adverse pressure gradient. The models in the prediction method are relatively simple and are based in part on the observed coherent structure of the time-dependent flow in the turbulent boundary layer. Note that the measured velocity and temperature profile data is predicted extremely well; in addition measured heat transfer rates and skin friction are predicted very closely. Modern asymptotic methods are used in the prediction method which is in this sense unique at present. This work is currently being extended in a rational manner to account for mainstream turbulence effects and is scheduled to be completed this summer. The objective of this part of the program is to develop the capability to be able to predict flows in the gas turbine environment.

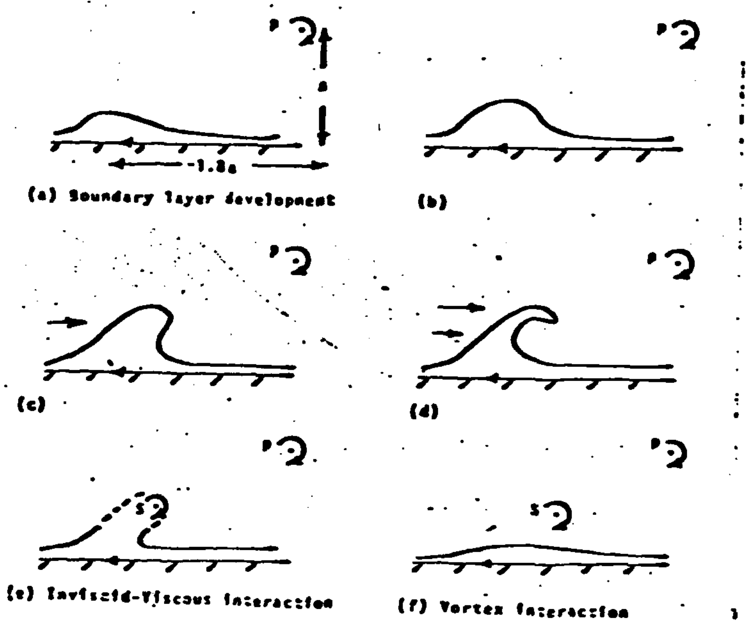

Figure 2. Sketch of proposed three phase vortex regenerative mechanism. (P and S denote parent and spawned vortices, respectively.)

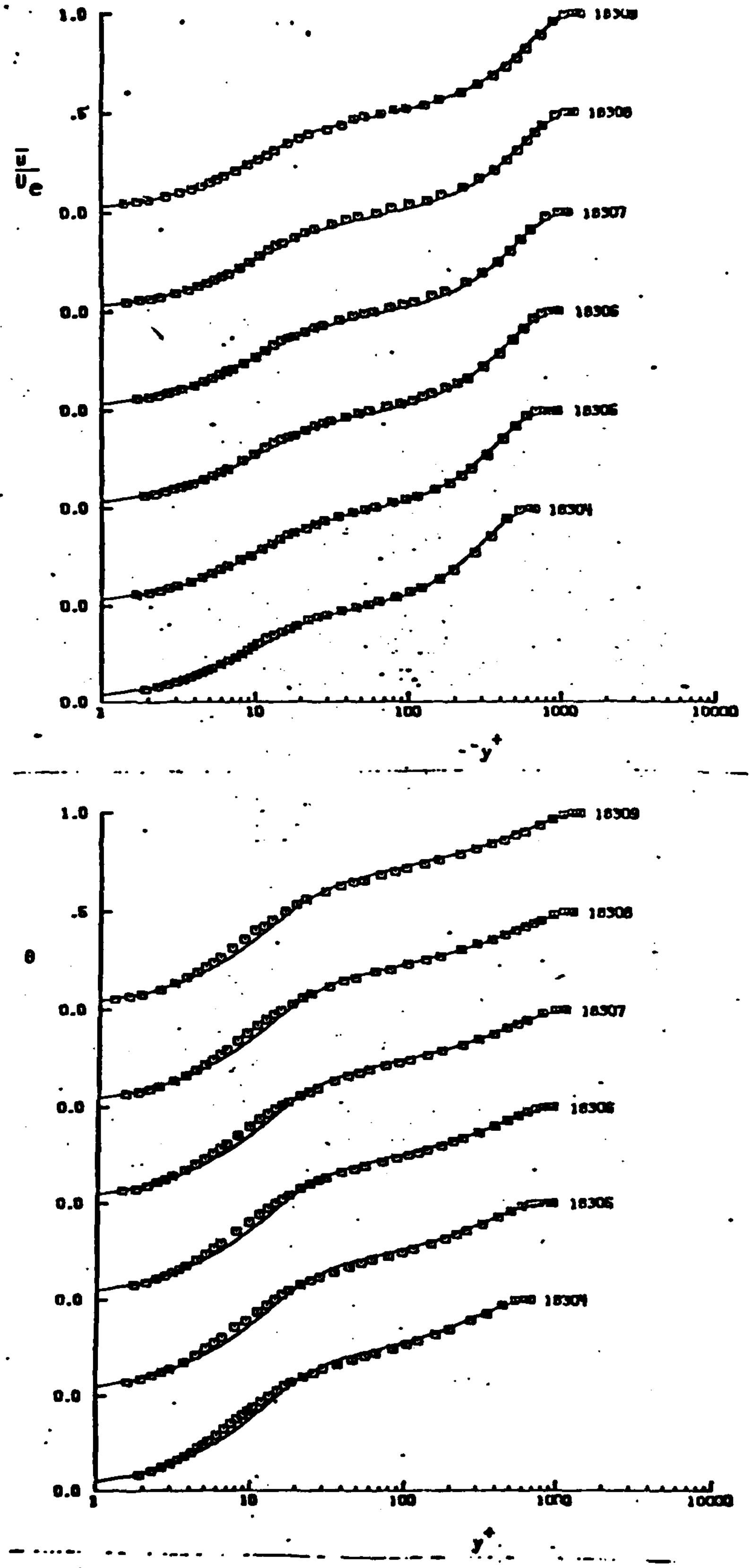

Figure 3. Prediction of veloctiy and temperature profiles in an adverse pressure gradient for a turbulent boundary layer.

At present, work is also currently underway to investigate the asymptotic structure and appropriate turbulence models for separated flow (in the time-mean sense) near a blunt trailing edge.

PREVIOUS ACCOMPLISHMENTS

Experimental Program

a) Was first experimental facility to employ video recording playback and moving reference frame observation of turbulent structure.

b) First study to demonstrate the existence of low speed pockets and to relate to low speed streak formation.

c) First study to demonstrate the ability of a convected vortex structure to promote a burst-like behavior.

d) First study to experimentally demonstrate the interaction of an impinging vortex on a viscous boundary layer.

e) Visually confirmed the existence of strong axial vortices in a turbulent boundary layer, documenting their flow characteristics.

Analytical Program

a) Developed a unique unsteady wall layer model for describing the mean profile in a turbulent boundary layer.

b) Developed both 1) a fast and accurate turbulent boundary layer prediction method and 2) the simplified turbulence models required for a).

c) Was the first analytical effort to elucidate the effects of vortex motion on boundary layers, which has particular implications with regard to aircraft trailing vortices and turbulent boundary layers.

TECHNOLOGICAL SIGNIFICANCE

The principle objectives of the present research program are (a) to develop an understanding of the fundamental mechanisms of turbulent boundary layer flows through a combined theoretical and experimental investigation and (b) from this understanding to develop improved techniques for the prediction of the time-mean behavior of such flows. The present program has successfully identified the effect that vortex motion induces in viscous boundary layers; previously this effect was largely unknown, and is that a boundary layer will ultimately erupt in response to vortex motion above it. Such information is important in the development of mechanical means for drag reduction and boundary layer control. Also under the current program, a prediction method is being developed which is consistent with the observed structure of the turbulent boundary layer. The unsteady wall layer model developed under this program is currently being used at Detroit Diesel Allison, Division of GMC in an Air Force sponsored program; here a prediction method for end wall boundary layers in compressors is being developed with the objective of predicting blockage effects due to the boundary layers on the hub and shroud of a compressor. A method of data reduction (using the unsteady wall layer model) is currently being used in an experimental program at United Technologies Research Center in evaluating and representing velocity and temperature profile data. Turbulence models for the transport of heat and momentum in the outer region of a turbulent boundary layer are also under development in the current program and it is planned to use these models in the near future in a new UTRC prediction program. A primary objective here is to develop the capability to predict skin friction and heat transfer effects on gas turbine blades. The development of models and techniques to calculate trailing edge flow separation on turbine blades is in progress under the current program in collaboration with UTRC.

In addition to supplying basic modeling information for the analytical effort, the experimental program is developing a tremendous insight into the physics of the turbulence generation process. In particular, experimental determination of specific flow elements occurring within a turbulent boundary layer has been achieved such that control of specific flow elements by surface modification techniques can and are being investigated. This will result in more rational methods for boundary layer control and turbulence augmentation/suppression which will in turn allow controlled modification of surface drag, as well as heat and mass transfer. In addition, the present studies are leading to investigations of methods for modifying the turbulence physics to improve conditions at or near boundary layer separation. Such information will allow rational approaches for form drag reduction to be developed which utilize an understanding flow structure control.

ASSOCIATED PUBLICATIONS, PRESENTATIONS AND THESES

Publications

[1] Walker, J.D.A., "The Boundary Layer due to Rectilinear Vortex" Proc. R. Soc. Lond. A., Vol. 359, 1978, pp. 167-188.

[2] Doligalski, T.L. and Walker, J.D.A., "Shear Layer Breakdown Due to Vortex Motion," Proceedings of the AFOSR Workshop on Coherent Structure of Turbulent Boundary Layers, C. Smith and D. Abbott, eds., Lehigh University, November, 1978, pp. 288-339.

[3] Doligalski, T.L., Smith, C.R. and Walker, J.D.A., "A Production Mechanism for Turbulent Boundary Layer Flows", presented at the "Symposium on Viscous Drag Reduction" Vought Advanced Technology Center, Dallas, Texas, Nov. 7 and 8, 1979, to be published in "Progress in Astronautics and Aeronautics".

[4] Walker, J.D.A., "Position Paper for Colloquium on Turbulent Flow Separation", SQUID Colloquium on Turbulent Flow Separation, January 18-19, Southern Method. University, (to be published in SQUID report), 1979.

[5] Smith, C.R., Brown, J.J. and Crosen, D.A., "Hydrogen Bubble-Wire Simulation of a Transverse Vortex in a Turbulent Boundary Layer," Technical Report CFMTR-78-2, School of Mechanical Engineering, Purdue University, April 1978.

[6] Smith,C.R., "Visualization of Turbulent Boundary-Layer Structure Using a Moving Hydrogen Bubble-Wire Probe," Proceedings of the Workshop on Coherent Structure of Turbulent Boundary Layers, Lehigh University, May, 1978.

[7] Smith, C.R. and Abbott, D.E., Proceedings of Workshop on Coherent Structure of Turbulent Boundary Layers, Lehigh University, November 1978.

[8] Smith, C.R., Schwartz, S.P. Metzler, S.P., and Cerra, A.W., "Video Flow Visualization of Turbulent Boundary Layer Streak Structure," Proceedings of the International Symposium on Flow Visualization, W. Merzkirch, Ed., Bochum, W. Germany (to be available June 1980).

PRESENTATIONS

J.D.A. WALKER

1. "Shear Layer Breakdown due to Vortex Motion", AFOSR Workshop on Coherent Structure of Turbulent Boundary Layers, Bethlehem, PA, May, 1978.

2. "Survey of Analytical and Experimental Investigation of the Coherent Structure of Turbulent Boundary Layers", invited seminar, United Technologies Research Center, East Hartford, Connecticut, June, 1978.

3. "The Effect of Vortex Motion on Wall Boundary Layers", First Annual Specialists Workshop on Coherent Structure of Turbulent Boundary Layers, Stanford, California, July 24, 1978.

4. "Some Aspects of Turbulent Boundary Layer Separation", SQUID Colloquium on Turbulent Flow Separation, Southern Methodist University, July 19, 1979.

5. "Boundary Layer Eruptions induced by Vortex Motion", Second Annual Specialists Workshop on Coherent Structure of Turbulent Boundary Layers, East Lansing, Michigan, July 29, 1979.

6. "A Production Mechanism for Turbulent Boundary Layer Flows", Symposium on Viscous Drag Reduction, Dallas, Texas, November 7, 1979.

7. "The Boundary Layer due to a Vortex Convected in a Shear Flow", 32nd Annual Meeting, Division of Fluid Dynamics, American Physical Society, Notre Dame, Indiana, November 18, 1979.

8. "Vortex Wall Interactions", invited seminar, The Ohio State University, Columbus, Ohio, May 30, 1980.

C.R. SMITH

1. "Visualization of Turbulent Boundary-Layer Structure Using a Moving Hydrogen Bubble-Wire Probe," Workshop on Coherent Structure of Turbulent Boundary Layers, Bethlehem, Pennsylvania, May 1978.

2. "Visualization of Coherent Turbulence Structure Using Conventional Video Technique," First Annual Specialists Workshop on Coherent Structure of Turbulent Boundary Layers, Stanford, California, July 24, 1978.

3. "High-Speed Video Analysis of Flow Visualized Turbulence Structure," Second Annual Specialists Workshop on Coherent Structure of Turbulent Boundary Layers, East Lansing, Michigan, July 28, 1979.

4. "The Visualization of Localized, Convected Fluid Pockets in the Wall Region of a Turbulent Boundary Layer," 31st Annual Meeting, Division of Fluid Dynamics, American Physical Society, Los Angeles, California, November, 1978.

5. "Visualization of Turbulent Boundary-Layer Structure Using a Moving Hydrogen Bubble-Wire Probe and a T.V. Viewing System," invited seminar, Penn State Department of Mechanical Engineering, May 3, 1979.

6. "A Production Mechanism for Turbulent Boundary Layer Flows," Symposium on Viscous Drag Reduction, Dallas, Texas, November 7, 1979.

7. "Streak Formation in Turbulent Boundary Layers: Recent Observations," 32nd Annual Meeting, Division of Fluid Dynamics, American Physical Society, Notre Dame, Indiana, November 1979.

8. "Experimental Observation of Vortex Loop-Boundary Layer Interactions," 32nd Annual Meeting, Division of Fluid Dynamics, American Physical Society, Notre Dame, Indiana, November 1979.

9. "Video Flow Visualization of Coherent Structures in a Turbulent Boundary Layer", invited seminar, University of Maryland Fluid Mechanics Seminar Series, 7 March, 1980.

10. "The Presence of Axial Vortices in Turbulent Boundary Layers: A Visual Study," invited talk, Ohio State University Colloquium on Turbulent Boundary Layer Structure, 21-23 March, 1980.

D.E. ABBOTT

1. "Theoretical and Experimental Investigation of Turbulent Boundary-Layer Structure-An Integrated Research Program," Thermal-Science Colloquium, Rutgers University, October, 1978.

2. "Investigation of the Fundamental Structure of Turbulent Boundary Layers," Ingersoll-Rand Corp., Phillipsburg, N.J., December, 1978.

3. "Specialists Workshop on Coherent Structure in Turbulent Boundary Layers", panalist, East Lansing, Michigan, July, 1979.

4. "Review of the A.F.O.S.R.-Lehigh University Program on Turbulent Boundary Layers," Lehigh University Research Center's Review, September, 1979.

5. "Boundary Layers," Technical Session Chairman, 32nd Annual Meeting, Division of Fluid Dynamics, American Physical Society, Notre Dame, Indiana, November, 1979. (Also elected Fellow, American Physical Society.)

THESES COMPLETE

Scharnhorst, R.K., "An Analysis and Preduction of Nominally Steady, Two-Dimensional, Constant Property Turbulent Boundary Layer", Ph.D. thesis, Purdue University, Aug. 1978.

THESES IN PROGRESS (expected completion date in parentheses)

1. Doligalski, T.L., "The Response of a Boundary Layer to Vortex Motion", Ph.D. thesis, (Aug. 1980).

2. Yuhas, L.J., "Prediction of Mainstream Turbulence Effects on Turbulent Boundary Layers", MSME thesis, (Aug, 1980).

3. Lee, W.C., "An Accurate Numerical Method for the Boundary Layer Equations", MSME thesis, (Aug. 1980).

4. Bogucz, E.A., "Separation of Turbulent Boundary Layers", Ph.D. thesis, (Aug., 1982).

5. Metzler, S.D. (M.S.), "A Critical Evaluation of the Visual Detection and Relationship of Low Speed Streaks and Bursting in Turbulent Boundary Layers," (August 1980).

6. Schwartz, S.P. (M.S.), "The Detection and Quantification of Axial Vortices in the Wall-Region of a Turbulent Boundary Layer," (August 1980).

7. Cerra, A.W. (M.S.), "Vortex Loop-Boundary Layer Interaction," (December 1980).

8. Wei, T. (M.S.), "Determination of Turbulence Flow-Field Characteristics Using a Digitized Flow Visualization Technique," (December, 1981).

6. REPORTS AND PUBLICATIONS

None since last annual report dated 31 December 1979.

7. OTHER SUPPORTING GRANTS & CONTRACTS

None at present.

8. PERSONNEL

Co-Principal Investigators

D.E. Abbott, Professor and Chairman of Mechanical Engineering
C.R. Smith, Associate Professor of Mechanical Engineering
J.D.A. Walker, Associate Professor of Mechanical Engineering

Student Research Assistants

		(Comp. date)
E.A. Bogucz	Ph. D. Candidate	(Aug. 1982)
T.L. Doligalski,	Ph. D. Candidate	(Aug. 1980)
A.W. Cerra,	MSME Candidate	(Dec. 1980)
L.W. Lee,	MSME Candidate	(Aug. 1980)
S.D. Metzler,	MSME Candidate	(June, 1980)
S.P. Schwartz	MSME Candidate	(Aug. 1980)
T. Wei	MSME Candidate	(Dec. 1981)
L.J. Yuhas	MSME Candidate	(Aug. 1980)

9. HONORS, AWARDS, & DEGREES

None since last annual report dated 31 December 1980.